Spatial and Temporal Variation in a Perched Headwater Valley in the Blue Mountains: Solar Radiation and Temperature

W. N. HOLLAND, D. H. BENSON and R. H. D. MCRAE

HOLLAND, W. N., BENSON, D. H., & MCRAE, R. H. D. Spatial and temporal variation in a perched headwater valley in the Blue Mountains: solar radiation and temperature. *Proc. Linn. Soc. N.S.W.* 113 (4), 1992: 297-309.

Solar radiation in a perched headwater valley in the Blue Mountains is calculated using slope and aspect and the results are compared with measured temperature variations. The calculated solar radiation and temperature values are each examined for spatial and temporal variations within the valley. The model predicts some spatial and temporal relationships, particularly differences between north and south-facing slopes but also between east and west-facing slopes. Solar radiation appears to be the main factor in valley asymmetry although the precise mechanisms at work are not known. This explanation provides a unifying framework to cover the whole period of valley development.

W. N. Holland, 143 Livingstone Avenue, West Pymble, Australia 2073, D. H. Benson, National Herbarium of New South Wales, Royal Botanic Gardens, Sydney, Australia 2000 and R. H. D. McRae, A.C.T. Bushfire Council, Tuggeranong, Australia 2901; *manuscript received 29 January 1991, accepted for publication 6 November 1991.*

INTRODUCTION

In a typical perched headwater valley in the Blue Mountains — Cold Foot Creek (lat. 33°40′S, long. 150°21′E) — landforms, vegetation, soils and hydrology are affected by the underlying rock strata (Holland *et al.*, 1992). But there are other significant spatial and temporal variations not related to rock strata, including valley asymmetry, in the geomorphology, vegetation, soils and hydrology. Holland (1974) speculated that differential solar insolation could account for asymmetric north/south valley slopes in the Blue Mountains. He found that rock structure was not a consideration since regional dip is easterly. Furthermore, asymmetry also occurs in the Carboniferous rocks of Megalong Valley (20 km south west of Cold Foot Creek) which have no regular rock structure.

In this study we consider the effects of solar radiation and temperature in the Cold Foot Creek perched headwater valley. Solar radiation values are calculated to establish relative spatial differences across the valley and for various time zones. These results are compared with observed temperatures, to test the validity of the calculated solar radiation findings and to gain insights into the nature and extent of temperature variations.

METHODS

Solar radiation for the summer and winter solstices was calculated for each of the 31 sites (Fig. 1a) used by Holland *et al.* (1992), at 1200 h solar time. Tables (Philips 1983; Loewe, 1962), depending on aspect, slope, latitude and longitude were used. The calculations assume a cloudless sky and are for solar radiation falling on a surface at right angles to the solar beam. Solar time is used exclusively. For the summer solstice, 1200 h equals about 1157 h Eastern Standard Time, while for the winter solstice the correction is less than one minute. The calculations give values of solar radiation at sea level though Cold Foot Creek is at 930 m a.s.l. However, these assumptions are acceptable as the aim was to examine relative position and time differences. Variations resulting from latitude and longitude differences within the study area have been disregarded as they are less than the order of accuracy achieved.

Values were also calculated throughout the day on each of the summer and winter solstices for sites 10 and 13. Further values, at 1200 h were calculated for selected sites, for the autumn equinox. Additional values at 1200 h were calculated for selected sites, for 11 days in December 1987.

Temperature is difficult to measure since it varies so much from place to place and over time. Continuous monitoring for long periods and concurrently at numerous sites was impractical so selected measurements were made at critical times to scan the various sites and time zones for trends. Comparisons are made on a relative basis and assume simultaneous recording and other conditions being equal. Measurements between September 1980 and December 1988 allowed sampling of a wide range of temperatures.

Surface temperatures for selected sites were measured over 15 days in summer (1987) and 13 days in winter (1987). Maximum/minimum thermometers were placed 50 mm above the surface, in the shade, and open to the air. Readings were taken throughout the day for sites 19 and 29 in June 1981, and for sites 10 and 13 in June and December 1987.

Additional temperatures were measured with thermometers 0.4 m below the surface at selected sites, for 11 days in summer (1987). These were measured inside 45 mm diameter perforated plastic pipes sunk to bedrock. The pipes were capped and further insulated from air temperature with foam within the pipes.

Relative humidity readings were calculated for sites 10 and 13, in June 1988 using a sling psychrometer held 1 m above the surface.

Wind readings about 1.6 m above the surface were taken for sites 10 and 13 in June 1988. A compass measured the direction of a blown woollen thread while speed was read from a device described by Linacre and Barrero (1975).

RESULTS

Calculated Solar Radiation

Spatial Variation

Values of calculated solar radiation of each individual site are a function of the angle of incidence of the sun's rays. Thus they are also a function of the geomorphology (i.e. they depend on aspect and slope). On north-facing sites the calculated solar radiation mean is significantly higher than the mean for south-facing sites on the summer and winter solstices (Table 1**a**). Because of the southern latitude of the study area, the sun always crosses the meridian in the northern sky. Thus the angle of incidence of the sun's rays is generally more on north-facing slopes than on those facing south. The range of calculated solar radiation values for all the north-facing sites is less than the range for the sites facing south (Table 1**b**). Since the ranges are functions of the aspect and slope of each site chosen for study they will vary from area to area.

There are also considerable differences in calculated solar radiation on east and west-facing slopes, depending on the season and time of day. This is discussed below, under daily changes.

Seasonal Changes

The mean value of calculated solar radiation in midsummer for all sites is significantly greater than the mean for midwinter. (Table 1**a**, Fig. 1). The range of values of calculated solar radiation for all the sites is less in midsummer than in midwinter (Table

1b). Again, this is a function of the high angles of incidence of the sun's rays in midsummer.

Calculated solar radiation values for some sites in a north/south trending section across the valley (S-N, Fig. 2**a**) show that the highest value for midsummer is at site 13 and for midwinter at site 14 (Table 3). Each of these sites are on the convex north-facing slope. The lowest value is for site 9 on the convex south-facing slope, in both midsummer and midwinter.

TABLE 1

Calculated solar radiation (Wm^{-2}) for all sites, at 1200 h solar time, for summer and winter solstices, and comparison of north and south-facing sites

(a) Means (± s.e.m.)

	Summer	n	Winter	n
All sites	26.3 ±0.12	31	11.1 ± 0.37	31
N-facing	26.9 ± 0.03	13	13.3 ± 0.18	13
S-facing	25.9 ± 0.12	18	9.6 ± 0.31	18
	t = 7.3 P<0.001		t = 8.9 P <0.001	

(b) Range of values

	Summer	Winter
All sites	1.9	6.6
N-facing	0.3	2.4
S-facing	1.6	4.5

Daily Changes

During the day, the calculated radiation value for each site increases as the sun rises to its maximum elevation on the meridian, at midday. Solar radiation decreases as the sun's elevation diminishes in the afternoon. These changes are shown for sites facing north (13) and south (10), in midsummer and midwinter (Fig. 3).

Calculated solar radiation is greater on east-facing sites than on west-facing sites in the morning but in the afternoon the reverse applies. This is demonstrated by comparing morning and afternoon values for sites facing east (27) and west (30) in midsummer and midwinter (Table 2).

Calculated Solar Radiation and Temperature

The calculated radiations do not take into account the masking effects of vegetation, soil type, ground moisture, cloudiness or other physical features affecting surface temperatures (Rosenberg *et al.*, 1983). Nevertheless, there is a close relationship between calculated radiation and surface temperature. Separate regressions of the daily mean surface temperature on calculated radiation for selected sites in summer, winter and autumn for woodland and perennial swamp sites, are each statistically significant (Fig. 4). A regression of daily mean temperature below the surface against calculated radiation for selected sites, in summer at midday, is also significant (Fig. 5). Thus, even beneath the surface, differences related to calculated solar radiation are evident in temperature variations.

Temperature

Spatial Variation

A comparison of sites along section S-N (Fig. 2) reveals a number of significant correlations in surface temperature. The highest mean daily maximum temperature is on the convex north-facing slope (Table 4a). The lowest mean daily maximum temperature is on the convex south-facing slope. These results are compatible with the findings for calculated solar radiation values.

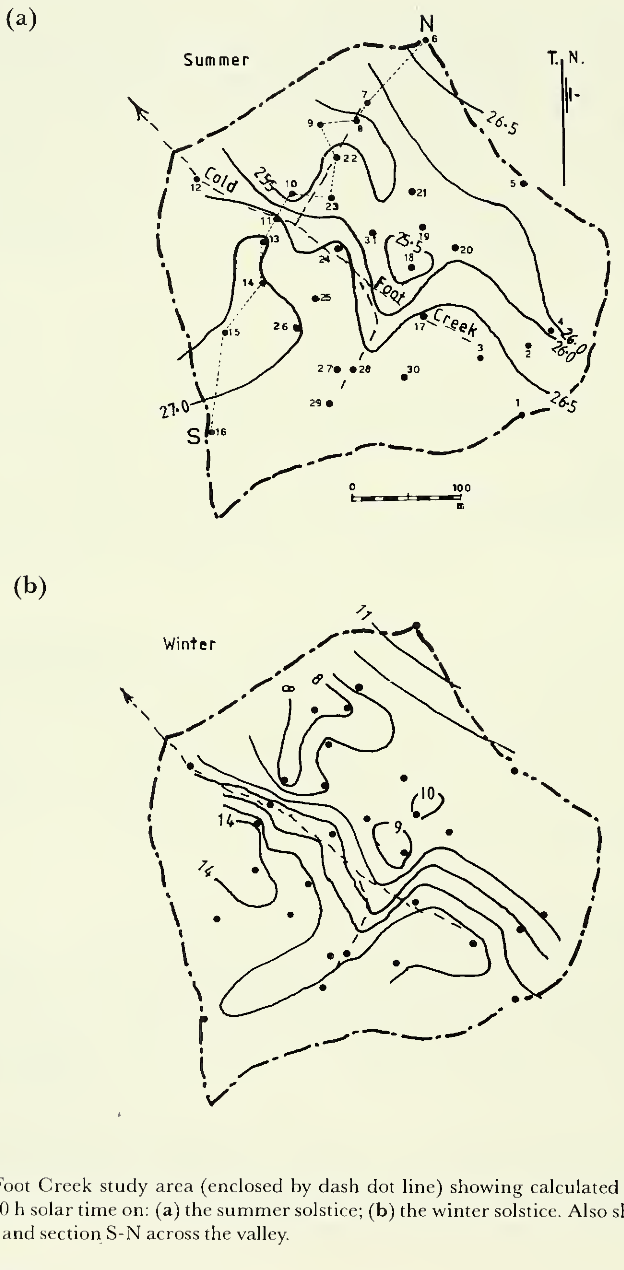

Fig. 1. Cold Foot Creek study area (enclosed by dash dot line) showing calculated solar radiation (Wm^{-2}) isolines at 1200 h solar time on: (**a**) the summer solstice; (**b**) the winter solstice. Also showing sites (numbered closed circles) and section S-N across the valley.

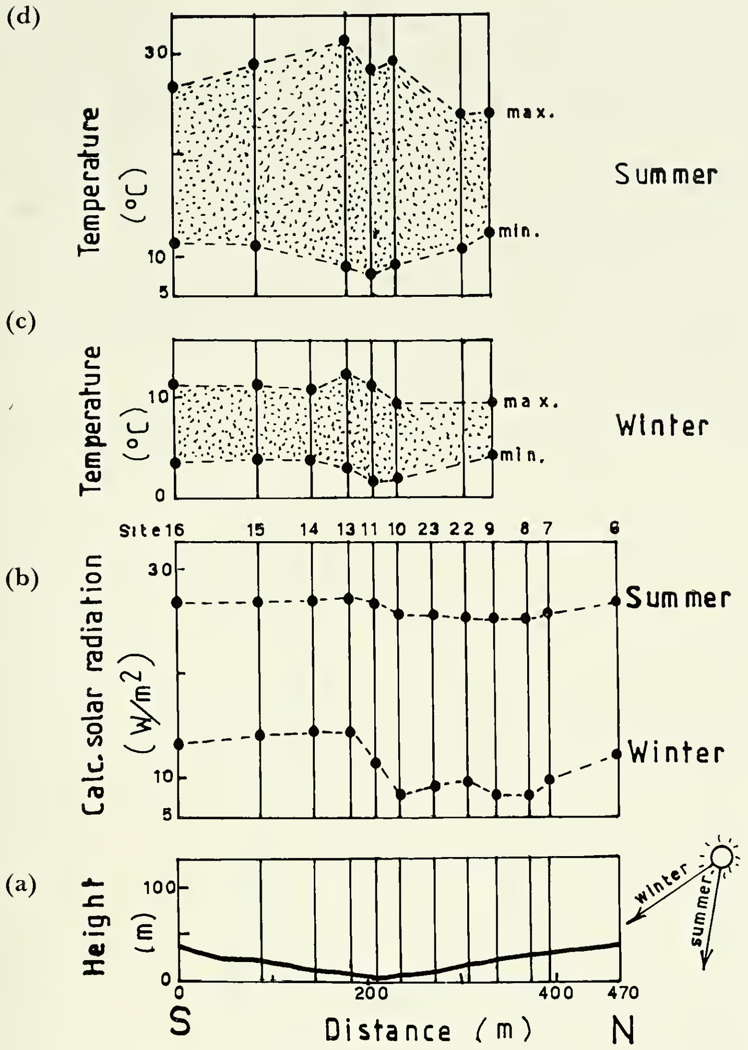

Fig. 2. Sites along section S-N (Fig. 1a) showing: (a) heights (m) and elevation of sun at 1200 h on the summer and winter solstices; (b) calculated solar radiation (Wm^{-2}) values at 1200 h solar time on the summer and winter solstices; (c) temperature (°C), daily maximum and minimum means, in winter (n=13 days), 16 June-6 July 1987; (d) temperature (°C), daily maximum and minimum means in summer (n=15 days), 2 December-28 December 1987.

TABLE 2

Calculated solar radiation (Wm^{-2}), at 0800 and 1600 h solar time, for east-facing site 27 (aspect 66°) and west-facing site 30 (aspect 337°), on summer and winter solstices

	Summer		Winter	
Site, Aspect	0800	1600	0800	1600
27 (E-facing)	15.4	11.9	3.3	1.1
30 (W-facing)	13.0	14.3	2.2	2.6
	+2.4	-2.4	+1.1	-1.5

The highest mean daily minimum temperature is on the convex north-facing slope. The lowest mean daily minimum temperature is on the convex south-facing slope in midsummer (site 9) but on the valley floor in midwinter (site 11). By contrast the lowest value of calculated solar radiation was for site 9 on the convex south-facing slope (Table 3**b**). Probably a physical factor such as cold air drainage lowers temperatures on the valley floor. This is supported by the finding that the daily mean difference between maximum and minimum temperatures is greater for site 11 than for site 9 in midsummer and midwinter (Table 4**c**).

North-facing slopes generally have higher temperatures than slopes facing south (Table 4**b**). However, the range of values between maximum and minimum is greater for south-facing slopes than for those facing north. These results are compatible with the findings for calculated solar radiation. Higher values on north-facing sites are found in both woodland and perennial swamp sites (Table 4**d**).

Daily mean minimum temperatures were higher in the woodland than in the perennial swamp (Table 4**e**). This circumstance is clearly influenced by cold air

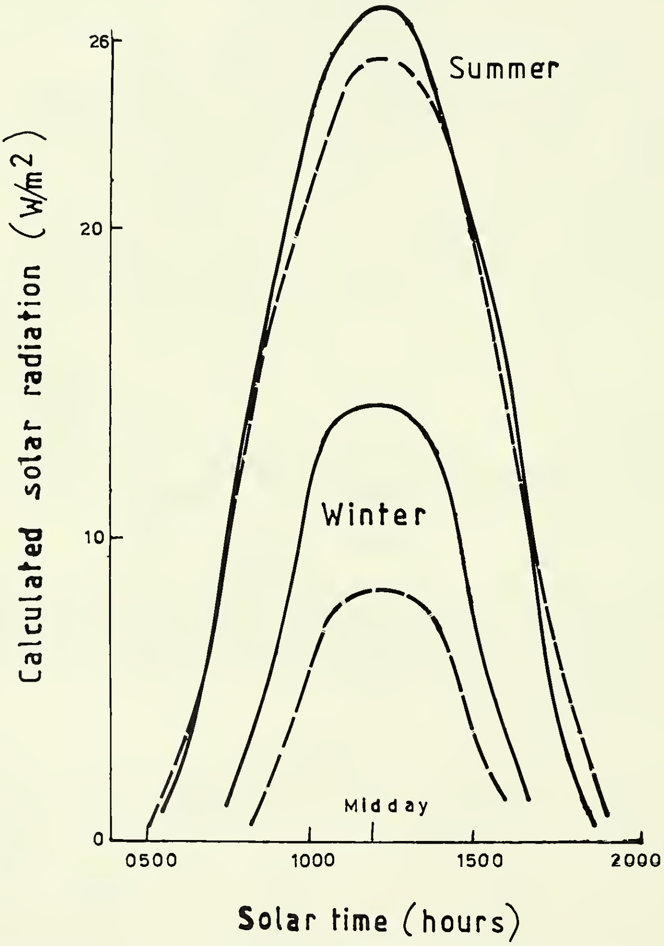

Fig. 3. Calculated solar radiation (Wm^{-2}) for site 13 (north-facing, shown by firm line) and 10 (south-facing, shown by dashed line) on the summer (longest day) and winter (shortest day) solstices.

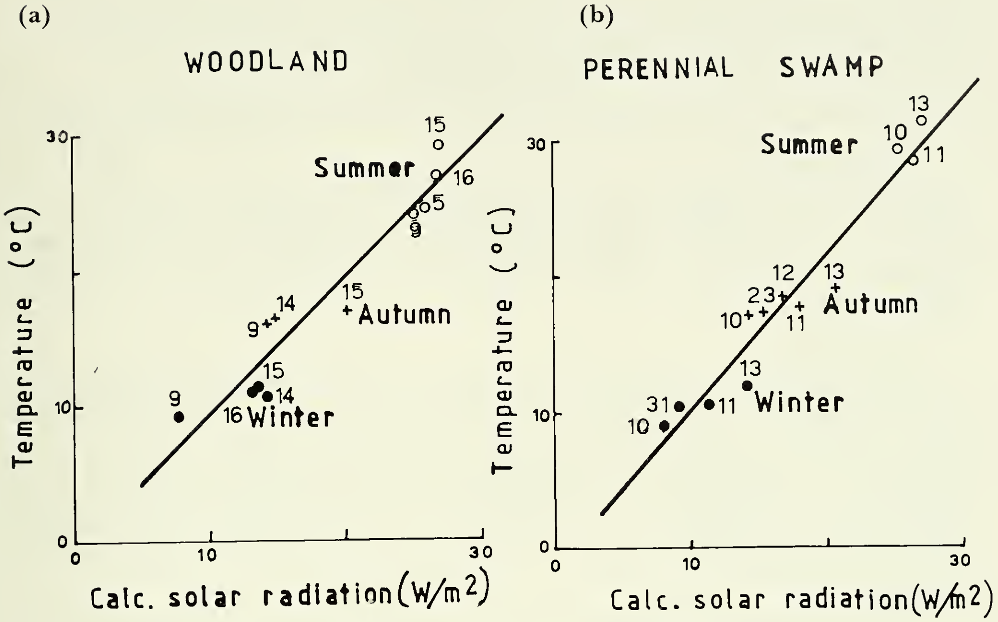

Fig. 4. Regressions of daily mean maximum surface temperature (°C) on calculated solar radiation (Wm^{-2}), at 1200 h solar time, for selected sites on the summer and winter solstices and autumn equinox: (a) woodland sites, where temperature = 0.053 calculated solar radiation — 0.795, coefficient of determination = 0.911, n = 11, and $P < 0.001$; (**b**) perennial swamp sites, where temperature = 0.060 calculated solar radiation — 1.277, coefficient of determination = 0.944, n = 12 and $P < 0.001$.

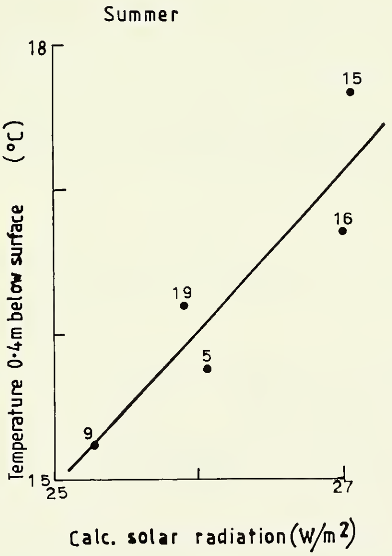

Fig. 5. Regression of daily mean maximum temperature (°C) 0.4 m below the surface on calculated solar radiation (Wm^{-2}), at 1200 h solar time, for selected woodland sites, for 11 days in summer (2-17 December 1987) where log temperature, 0.4 m below the surface = 1.746 log calculated solar radiation — 1.265, r^2 = 0.81, n = 5 and $P < 0.05$.

drainage and other physical factors which may include the relative insulation effects of different vegetation cover.

In readings taken 0.4 m below the surface north-facing slopes had significantly higher temperatures than south-facing slopes (Table 5).

Temperature differences between east and west-facing sites are discussed below.

Seasonal Changes

The daily mean temperature range (daily mean difference between maximum and minimum) was significantly greater in midsummer than midwinter (Table 4**f**). The daily mean maximum and minimum temperature ranges (i.e. between highest and lowest daily readings) were both significantly greater in midsummer than in midwinter (Table 4**g**, 4**h**).

Daily Changes

Daily variations in midsummer and midwinter temperatures (Fig. 6) demonstrate the lag between peak solar radiation and surface temperature. This results from the balance between net incoming and outgoing radiation, and the effect on temperatures of shielding by topography and vegetation. (We cannot explain the lowering of the temperatures at noon, for site 13, in winter (Fig. 6). The only other changes noted between 1100 and 1200 hours were an increase in cloud cover from 30% to 60%, a decrease in relative humidity from 11.4% to 8.2% and an increase in wind speed (from 3 to 5 kmh^{-1}).

Daily temperatures measured 0.4 m below the surface are less variable than surface temperatures as the direct effect of solar radiation is damped down by vegetation cover and soil. Measurements in summer, (sites 9 and 15) show significant regressions of the difference between mean maximum surface temperature and temperature 0.4 m below the surface on mean maximum surface temperature (Fig. 7).

There is also a contrast (albeit of smaller magnitude to north/south asymmetry) between east and west-facing slopes. The morning sun warms east-facing slopes more than those facing west. In the afternoon this is reversed (Fig. 8, Table 2). Site 29 (aspect 249°) shows higher temperatures all day than site 19 (aspect 46°) as expected from their respective north/south orientations. However, because they also face respectively east and west, site 29 heats up more rapidly than 19 in the morning and cools off more rapidly in the afternoon. Site 29 also maintains its midday peak longer than site 19 from the additional warming in the morning.

TABLE 3

Calculated solar radiation (Wm^{-2}) for sites along section S-N (Fig. 2), on summer and winter solstices, and comparison of north and south-facing sites

(a) Means (± s.e.m.)

	Summer	n	Winter	n
N-facing	27.0 ± 0.05	5	13.4 ± 0.40	7
S-facing	25.7 ± 0.16	5	8.9 ± 0.43	7
	t = 6.1	P<0.001	*t* = 6.9	P<0.001

(b) Range of values

	Summer		Winter	
	N-facing	S-facing	N-facing	S-facing
Highest	27.1 (13)	26.6 (11)	14.3 (14)	11.3 (11)
Lowest	26.8 (6)	25.3 (6)	11.9 (6)	7.7 (9)

TABLE 4

Daily maximum and minimum surface temperature (° C), means (± s.e.m.), and individual temperature (° C) values for sites on section S-N (Fig. 2), over 19 days in summer (2 December-28 December 1987) and 15 days in winter (16 June-6 July 1987)

(a) Range of individual daily max. and range of individual daily min. temperatures for both summer and winter

	Summer		Winter	
	Max.	**Min.**	**Max.**	**Min.**
Highest	37.8 (site 13)	26.3 (13)	15.5 (15)	9.5 (15)
Lowest	6.5 (9)	3.5 (9)	6.0 (9)	-4.5 (11)
Range	31.3	22.8	9.5	14.0

(b) Range of individual daily max. temperatures for summer and winter, and for north and south-facing sites

	Summer		Winter	
	N-facing	**S-facing**	**N-facing**	**S-facing**
Highest	37.8 (site 13)	34.5 (9)	15.5 (15)	14.0 (11)
Lowest	13.8 (13)	6.5 (9)	8.0 (15)	6.0 (9)
Range	24.0	28.0	7.5	8.0

(c) Comparison of daily mean difference between max. and min. temperatures for a south-facing site (9) and a valley floor site (11), in summer and winter.

	Summer	**n**	**Winter**	**n**
Site 11 (valley floor)	17.8 ± 1.3	19	9.1 ±0.8	13
Site 9 (S-facing)	10.8 ± 1.0	18	5.4 ± 0.4	13
	$t = 4.0$ $P<0.001$		$t = 3.9$ $P<0.001$	

(d) Daily mean difference between max. temperatures for paired sites

	Summer				Winter			
		n	**t**	**P<**		**n**	**t**	**P<**
Perennial swamp (13N-10S)	2.8 ± 0.4	17	6.9	0.001	2.8 ± 0.3	12	8.1	0.001
Woodland (15 N-9S)	4.5 ± 0.6	19	7.0	0.001	1.8 ± 0.3	13	6.6	0.001

(e) Daily mean min. temperatures for summer and winter

	Summer	**n**	**Winter**	**n**
Woodland	11.6 ± 0.4	3	3.6 ± 0.1	4
Perennial swamp	8.6 ± 0.3	3	2.0 ± 0.4	3
	$t = 6.2$ $P<0.005$		$t = 3.9$ $P<0.02$	

(f) Daily mean temperature range (daily mean difference between max. and min. temperatures).

Summer	**n**	**Winter**	**n**	**t**	
16.8 ± 1.3	8	7.7 ± 0.4	8	6.1	$P<0.001$

TABLE 4 (Cont'd)

(g) Daily mean maximum temperature range in summer and winter

	Summer	n	Winter	n
Highest	31.4 ± 1.1	15	11.8 ± 0.5	13
Lowest	23.9 ± 1.1	15	9.0 ± 0.6	13
	$t = 14.6$ $P<0.001$		$t = 3.5$ $P<0.005$	

(h) Daily mean minimum temperature range in summer and winter

	Summer	n	Winter	n
Highest	12.2 ± 0.8	15	3.8 ± 0.7	13
Lowest	7.9 ± 1.0	15	1.5 ± 1.0	13
	$t = 3.3$ $P<0.005$		$t = 1.8$ $P<0.10$	

TABLE 5

Daily temperature (° C), means (± s.e.m.),
0.4 m below the surface at sites 9 and 15,
about 0800 h solar time (30 November-28 December, 1987

Site, Aspect	Temperature	n
15 (N-facing)	17.7 ± 0.3	20
9 (S-facing)	15.9 ± 0.2	20
	$t = 4.2$ $P<0.001$	

DISCUSSION

It is surprising that the differential amounts of solar radiation received at individual sites, as a result of the movement of the sun, has received scant attention in geomorphology textbooks. Treatment of the subject is usually on a broad brush approach (Thornbury, 1954; Selby, 1982). Selby, for example, notes that the sun is the prime energy source but does not pursue the matter of differences which occur from place to place and over time.

This study, together with our other investigation (Holland *et al.*, 1992) has revealed significant differences between the environments of north and south-facing sites. These differences include slopes (north-facing less steep), temperatures (north-facing generally warmer but south-facing sites having a greater range of temperatures), hydrology (greatest fluctuation of water depths on north-facing swamp sites) and vegetation (some differentiation in species and degree of species richness).

It would be dubious science to conclude that any of the differences demonstrated result in solar radiation effects which 'stress' the environment. However, most of the differences detected will always be in the one direction e.g. north-facing slopes will always tend to be warmer than south-facing slopes because of the sun's position relative to the earth. Further, the sun has moved in its path continuously for a long time. The differences are incremental and have occurred over a long period of time. It is not unrealistic to speculate that subtle changes could occur in the micro-environments in response to the differences noted, and of any other undetected differences f n varying solar radiation intensity. In any event all the differences noted warrant seri consideration in studies of geomorphology or vegetation. Further, if these differer s do affect (say) slope, then at some point in time there is probably a feedback sit ion where alteration of a slope results in a new set of solar radiation criteria. Sim feedback mechanisms apply to the vegetation and other aspects of the environme Our study

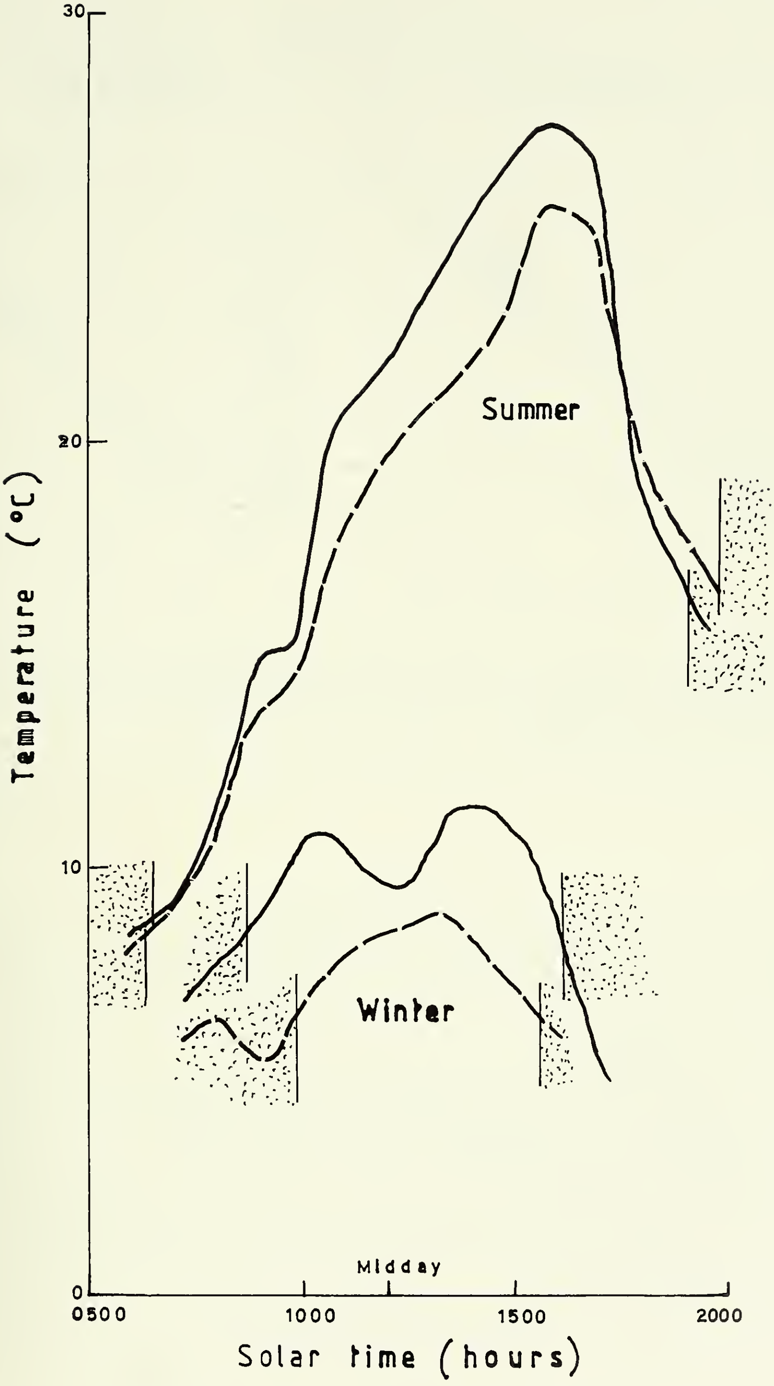

Fig. 6. Daily surface temperature (°C) range for sites 13 (north-facing, shown by solid line) and 10 (south-facing, shown by dashed line), in summer (23 December 1987) and winter (21 June 1988). Dotted areas show periods when the sun's rays were blocked by physical objects.

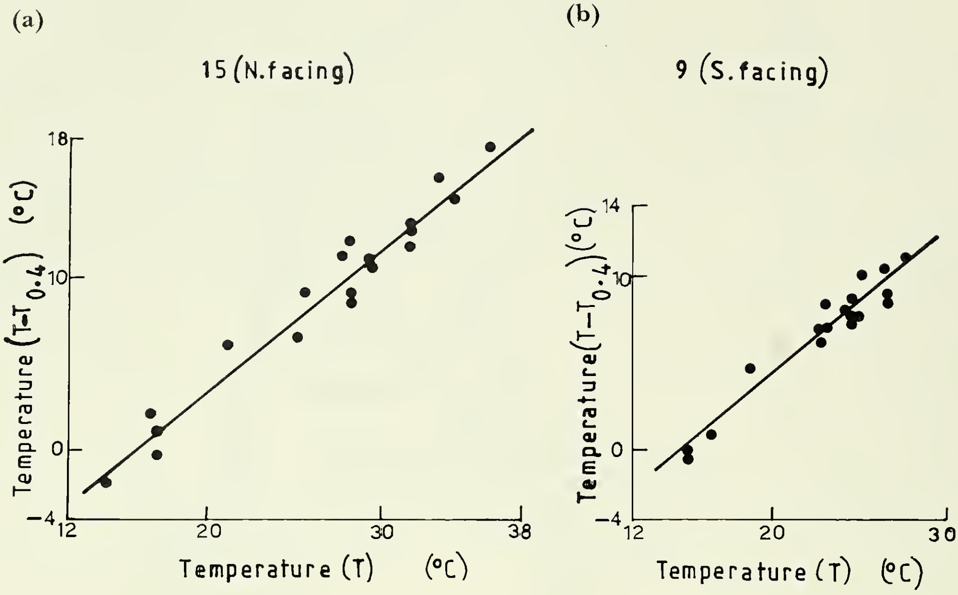

Fig. 7. Regressions of the difference between daily maximum surface temperature (T) and temperature 0.4 m below the surface ($T_{0.4}$), on T between 2 December and 28 December 1987: (**a**) site 15 (north-facing) where $T_{0.4} = 0.823\,T - 13.016$, $r^2 = 0.956$, $n = 19$ and $P < 0.001$; (**b**) site 9 (south-facing) where $T_{0.4} = 0.841\,T - 12.421$, $r^2 = 0.943$, $n = 18$, and $P < 0.001$.

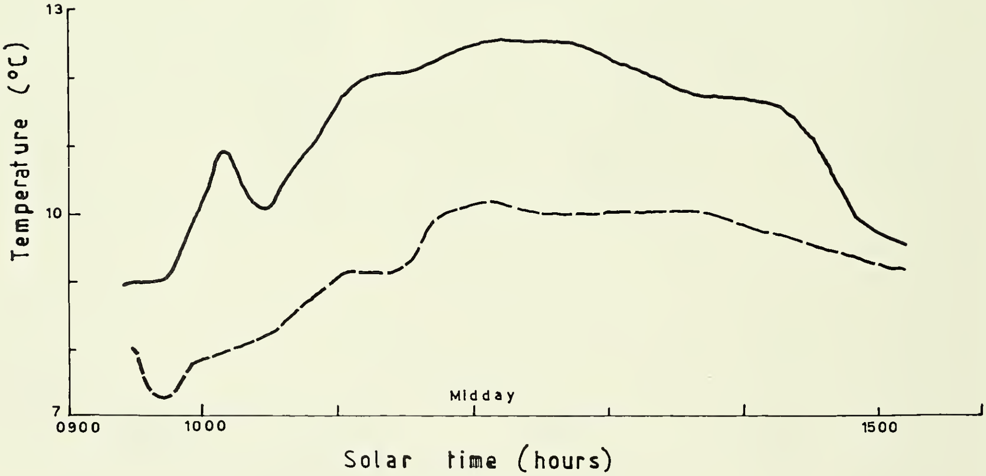

Fig. 8. Surface temperature (°C) for site 29 (E-facing, shown by solid line) and 19 (W-facing, shown by dashed line), on 28 June 1981.

has already established some such relationships e.g. the daily movement of groundwater levels which depend largely on evaporation from the sun's rays.

Calculated solar radiation using only aspect and slope measurements, has yielded useful correlations with temperature. These correlations concern differences in both position and time. From this it is possible to rank sites, with respect to expected radiation intensity and from this to anticipate temperature variations. When tested against temperature the results correlate well, suggesting that the model could be used for studying other environmental aspects. In practice, differences relating to aspect have long been recognized and incorporated in mapping vegetation areas, for example Keith and Benson (1988). Use of the calculated solar radiation model provides a means of easily ranking each site. Since micro-climates change so continuously and unpredictably, computer control is needed to handle the voluminous spatial and temporal data needed. This thinking also applies to soil analysis and mapping. From a research viewpoint, the demonstrated differences in solar radiation indicate the likely extent of radiation on a particular slope. It could enable research to be directed to comparing numerous factors such as soil texture or any other aspect of the soil profile which could be modified by variations in solar radiation from site to site and over different time zones. One key question which could be addressed is the precise mechanism which makes one slope greater than another one nearby.

ACKNOWLEDGEMENTS

The authors are grateful to the National Parks and Wildlife Service for permission to work in the Blue Mountains National Park. Thanks are also due to Mr N. Mickie for instrumentation to continuously record temperatures and for helpful discussion. Special thanks to Lois Holland for field assistance in all weathers, and to Peter, Bill and Lee Holland for additional field work. Thanks also to Ron Goldbery for critically reading the text, John Pickard for useful suggestions on the text and Len Smith for helpful discussion.

References

HOLLAND, W. N., 1974. — Origin and development of hanging valleys in the Blue Mountains, New South Wales. Sydney, N.S.W.: University of Sydney, Ph.D. thesis, unpubl.

——, BENSON, D. H., and MCRAE, R. H. D., 1992. — Spatial and temporal variation in a perched headwater valley in the Blue Mountains: geology, geomorphology, vegetation, soils and hydrology. *Proc. Linn. Soc. N.S.W.* 113 (4): 271-295.

KEITH, D. A., and BENSON, D. H., 1988. — The natural vegetation of the Katoomba 1:100 000 map sheet. *Cunninghamia 2*: 107-143.

LINACRE, E. T., and BARRERO, J. A., 1975. — Surveys of surface winds in the Sydney region. *Proc. 8th New Zealand Geog. Conf. and Internat. Geog. Union Conf.* Palmerston North, 247-260.

LOEWE, F., 1962. — The intake of solar radiation by slopes with cloudless sky, *Bur. Met. Bull.* (45).

PHILLIPS, R. O., 1983. — Sunshine and shade in Australasia. *Dept. Transport and Construction. Bull.* (8).

ROSENBERG, N. J., BLAD, B. L., and VERMA, S. B., 1983. — *Microclimate the Biological Environment.* New York: John Wiley & Sons.

SELBY, M. J., 1982. — *Hillslope Materials and Processes.* Oxford Univ. Press.

THORNBURY, W. D., 1954. — *Principles of Geomorphology.* New York: John Wiley & Sons.